AD-A125 237 INJECTION ATOMIZATION IGNITION AND COMBUSTION OF LIQUID FUELS IN HIGH-SPE..(U) VIRGINIA POLYTECHNIC INST AND STATE UNIV BLACKSBURG DEPT OF A.. J A SCHETZ NOV 82 VPI-AERO-130 AFOSR-TR-83-0025 AFOSR-78-3485 F/G 21/2

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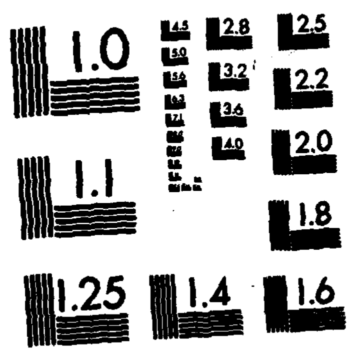

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AFOSR Final Scientific Report
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Nov. 1982
VPI-Aero-130

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR-TR- 83-0025	2. GOVT ACCESSION NO. AD-A125 237	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) INJECTION, ATOMIZATION, IGNITION AND COMBUSTION OF LIQUID FUELS IN HIGH-SPEED AIR STREAMS		5. TYPE OF REPORT & PERIOD COVERED Final Report 1 Dec 78 - 30 Nov 81
		6. PERFORMING ORG. REPORT NUMBER VPI-Aero-130
7. AUTHOR(s) J. A. SCHETZ		8. CONTRACT OR GRANT NUMBER(s) AFOSR-78-3485
9. PERFORMING ORGANIZATION NAME AND ADDRESS VIRGINIA POLYTECHNIC INSTITUTE & STATE UNIVERSITY AEROSPACE AND OCEAN ENGINEERING DEPARTMENT BLACKSBURG, VA 24061		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2308 A2 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA BOLLING AFB, DC 20332		12. REPORT DATE November 1982
		13. NUMBER OF PAGES 21
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

RAMJETS
LIQUID JETS
COMBUSTORS
SLURRIES

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Experimental studies of the penetration, break-up and atomization of transverse liquid and slurry jets were performed. All tests were with an air cross flow at Mach 3.0 with P_o = 4 atm. and T_o = 300°K. The processes studied were: 1) the effects of injectant viscosity and surface tension, 2) the performance of an impinging jet injector and 3) the effects of particle loading for a slurry jet with 3-50 μ particles. The diffractively scattered light method was employed at these high-density, supersonic conditions to study

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droplet sizes. The major results are, 1) mean droplet size is approximately 10 microns for injectors of 0.05 in., 2) it has an inverse relation with jet/free stream dynamic pressure ratio, 3) it has a direct relation with orifice diameter, 4) it decreases downstream, 5) transverse variation has no simple pattern and 6) droplet size increases with viscosity. Very high viscosities result in break-up into ligaments rather than droplets. Also, penetration is reduced with increasing viscosity. The impinging jet injector showed droplet sizes reduced by a factor of about two. Transverse jets in a dump combustor were studied. The location of the injector relative to the step had no effect on jet penetration and break-up. Substantial injectant accumulation in the base region was found under some conditions. Studies of particle-laden liquid jets show that the distance to breakup is substantially increased with increased particle loading. Increased particle loading also reduces the crossflow penetration of the liquid portion of the injectant. The separation of the solid and liquid phases of the injectant was documented.

Research Objectives

A high level of interest in the ramjet/scramjet field continues due to the potential performance benefits over other systems for missile, projectile and aircraft propulsion. The physical and chemical processes associated with transverse injection of liquid and/or liquid-slurry fuel jets into high speed airstreams find application in these and several other propulsion-related systems. For supersonic airstreams, these include thrust vector control and external burning in the wake region of projectiles, as well as scramjet engines. For subsonic airstreams, the other applications include "dump" combustors on devices such as integral rocket ramjets, afterburners and dumping of cooling water out the end of turbine blades, in addition to subsonic ramjet devices.

The important phenomena in all of these applications include physical processes associated with gross penetration, jet fracture and breakup and atomization, and, in some, chemical processes associated with ignition and combustion. Studies at Virginia Tech during the subject time period concentrated on various aspects of the complex physical processes involved.

Droplet Size Measurements in the Spray Plume

The Grantee was to undertake in-depth experimental studies of droplet size variations along and across the plume of liquid jets injected transverse to high-speed air streams. Different injectant port sizes and port shapes were to be tested over a range of injectant flow rates. Attention was to be directed at those parameters and conditions that produce significant drop size changes. Alcohol-water and glycerin-water solutions and other fluids were to be used to permit systematic variations in injectant viscosity and surface tension.

Particular attention was to be directed at the influence of viscosity on the mode of atomization - into droplets or into ligaments.

Slurry Jet Break-up

Basic studies of the break-up of a particle-laden liquid jet injected into quiescent air were to be undertaken. The details of the process were to be determined by systematic experimentation, and the results compared to those for the all-liquid case. The Grantee was also to conduct experimental studies of liquid/solid-particle, transverse jets in high speed air streams. Exploratory experiments were to be conducted at $M_\infty = 3.0$ over a range of flow rates (and hence $\bar{q}$).

Impinging-Jet Injectors

A study of the possible benefits with regard to fuel jet atomization of an impinging jet injector was planned and performed.

Status of the Research

Droplet Size Measurements in the Spray Plume

A detailed study of the effects of injectant properties on the break up and atomization of a transverse liquid jet in a supersonic airstream was conducted. The tests were run at Mach 3.0 with ambient stagnation temperature and a stagnation pressure of 4.2 atm. Viscosity and surface tension of the liquid injectant along with the injector diameter and the ratio of the jet to freestream dynamic pressures were individually varied and their effects on

the structure and the atomization processes of the jet were established. The investigation employed a short exposure (9×10^{-9} sec.) photographic technique to establish the instantaneous structure of the jet in the crossflow. Relatively long exposure (10^{-3} sec.) photographs were obtained to study the time-averaged behavior of the jet in the crossflow for jet penetration measurements. A multi-exposure photographic technique was used to study the windward edge of the jet. The important results are: 1) for cases of low viscosity and low surface tension, wave growth and cross fracture of the jet is the main mechanism of atomization, 2) for cases of high viscosity liquid jets, ligament formation is the principle mechanism for atomization, 3) increasing viscosity reduces wave growth on the jet surface, 4) jet penetration in the cross flow initially increases with increasing viscosity and then decreases, 5) jet penetration in the cross flow is essentially independent of surface tension, 6) surface tension has an insignificant effect on wave propagation speed, and liquid clump velocities, 7) increasing viscosity decreases the wave propagation speed, 8) liquid clump velocity is independent of viscosity and surface tension, 9) wave propagation speed is independent of $\bar{q}$.

The results have been presented in detail in AIAA Paper Nos. 81-0188 and 82.0253, both to be published in the AIAA Journal in the near future. Only a few selected results are included here.

Figure 1 shows nondimensional penetration h/d for pure water, water/alcohol and water/glycerine injectants as a function of the dynamic pressure ratio ($\bar{q}$). There is not a measurable penetration difference for the case of pure water and solutions of water/alcohol. However, the water/glycerine injectant shows a lower penetration than that for water alone.

The physical properties of the injectants such as surface tension and viscosity

determine the spray fineness. Each table contains four columns, x/d, y/d, h/d, D_{32}. The x/d entries are the nondimensional distance downstream of the injectant port. The y/d column shows the nondimensional distance measured from the surface of the flat plate. The values of x/d and y/d are the coordinate locations of the incident beam in the jet plume with respect to the injector orifice which is at the origin x/d = y/d = 0. The h/d entries are the non-dimensional penetration heights measured from the long exposure streak photographs. Finally, the D_{32} column entries are the measured droplet diameter at the stations (x/d, y/d) in the jet plume.

Table I shows the variations of droplet diameter in the jet plume for the case of pure water injectant at $\bar{q}$ = 12 with d = 0.45 mm. Measurements were taken along the jet from x/d = 10.9 to 207.7. The droplet diameter decreased as one moved downstream. For example, D_{32} = 15.4 microns at (x/d = 59.0 , y/d = 1/2, h/d = 11.6) which decreased to D_{32} = 14 microns at (x/d = 207.7, y/d = 1/2, h/d = 12). Also, the cross-plume measurements of droplet size revealed the fact that droplet diameter decreases to its smallest value near the boundaries of the plume. At x/d = 207.7, y/d was changed from 6.6 to 26.2 and the droplet diameter increased in size from 10 to 14 microns, then decreased to 10 microns again. The same holds true for cross-plume measurements taken at x/d = 59. At stations x/d = 10.9 and x/d = 21.9 the droplet sizes are small, which is due to the fact that very near the injector orifice the whole laser beam is not in the main jet, and the measurements are of the small particles that have been sheared away from the jet column.

Table II shows the droplet distribution for pure water injectant at $\bar{q}$ = 4 through the bigger injector. In order to help the reader understand

the nature of the variations in droplet size across and along the plume, we have prepared Fig. 2. This shows a scale drawing of the model and the locations and size of the laser incident beam. The droplet sizes obtained at each location are entered next to the measurement locations.

Table III shows the variation of droplet diameter across and along the jet due to injection of water/alcohol solution at $\bar{q} = 12$ through the small injector (d = 0.45 mm.) The surface tension of this injectant is roughly one half of the surface tension of pure water, but it has the same viscosity. Again, the droplet diameter decreases in size as one moves downstream from the injector port. However, the process of atomization seems to be more complete than that for pure water as there is not a great variation in droplet diameter throughout the plume. Also, the droplet diameters appear to be slightly smaller for the case of lower surface tension, keeping other variables constant.

Table IV shows the variation in droplet diameter in the water/glycerine jet plume which has been injected at $\bar{q} = 12$ through the middle-size (d = 0.96 mm.) injector. The viscosity of this water/glycerine solution is nine times greater than that of pure water, but it has the same surface tension as pure water. Again the study of droplet variation across and along the jet reveals that droplets are the smallest at or near the plume outer edges, and that droplet diameter decreases as one moves downstream of the injectors. Comparison of this data with that described earlier shows that an increase in viscosity, while holding other properties constant, increases the droplet diameter. Further, the process of atomization is not as uniform as for the water/alcohol injectants. There is a large variation in droplet diameter throughout the spray plume.

Solutions of water and glycerine can have extremely wide ranges of viscosities. The study of the effects of a very high viscosity injectant upon droplet diameter was not possible. From very short duration (10^{-8} sec.) spark photographs of the jet plume, it was found that higher viscosity injectants behave very differently from the lower viscosity injectants. The combination of high injectant viscosity and low $\bar{q}$ produces a break up into ligaments rather than droplets. For high enough $\bar{q}$, even the high viscosity injectants break up into droplets. The boundary between the two situations is rather sharp, and it is near $\bar{q} = 10$. This phenomena will surely be a fruitful area for further study. However, for the present effort, the occurrence of ligaments rather than droplets renders the DSLM (at least in its present, simple form) unusable.

Break-up of Liquid Slurry Jets

Some results of a two-part, experimental study of the behavior of particle-laden liquid jets injected into air have been obtained. The work to date has involved water as the liquid carrier and either 3-37μ diam. S_iO_2 with a specific gravity of 2.8-3.0 as the particles. The observations were mainly photographic. First, the break-up of jets injected into still air was investigated as a function of particle loading, and the results were compared to the pure liquid jet case. The jets were found to be more stable with particles present. The length to break-up was increased, and the formation of "satellite" droplets was suppressed. We have also developed a numerical procedure for the break-up of liquid-slurry jets based on the "Marker in Cell" method due to the workers at Los Alamos. The results will be detailed in AIAA Paper No. 83-0067. Second, the penetration and break-up of transverse jets in a Mach 3.0 air stream was studied. The general break-up mechanism of wave formation was found to be the same as for

the all-liquid case. Significant separation of the phases was observed, and the penetration of the liquid phase was reduced compared to all-liquid cases at the same value of the jet to free stream momentum flux ratio.

Penetration data for the liquid portion of the plume have been deduced from the $\bar{q} = 3$ tests with the larger particles, and the results are shown in Fig. 3. It can be seen that a slight decrease was found as particle loading was increased. One can postulate that this is due to the phase separation. The solid particles penetrate further than the liquid. Perhaps the trajectory of the center of mass of the injectant as a whole is similar to that for an all liquid jet. In any event, results of the type in Fig. 3 can be used in conjunction with existing penetration correlations for all-liquid jets over a wide variety of conditions and configurations for preliminary design purposes.

Further studies were made with particles that had an average diameter of 5 microns. Concentrations of particles of up to 60% by mass were tested. The results were presented in AIAA Paper No. 82-1260. The penetration of the particle-laden liquid jet was complicated due to the separation of some of the solid particles from the liquid plume. The nanoflash photographs clearly showed agglomerates of solid particles penetrating further into the cross flow than the liquid. This separation was evident in the streak pictures as a smearing of the penetration profile.

The penetration height is usually defined as the vertical extent of the densest portion of the jet as viewed in the streak photographs. For the slurry jets this height corresponded to the extent of the liquid portion of the jet. Attempts to base the penetration height upon the penetration of the particles yielded inconsistent results. The penetration height (for the liquid plume) was measured at a distance 30 jet diameters downstream of the injection orifice.

In Table V the penetration height is given as a function of the momentum flux ratio, $\bar{q} \equiv \rho_j v_j^2 (\rho_\infty v_\infty^2)^{-1}$, and the loading, defined as the percent of solid particles in the slurry by mass. For a given loading, the penetration height follows the usual relationship with the momentum flux ratio: as $\bar{q}$ is increased, the penetration height increases as well. If, on the other hand, $\bar{q}$ is held constant as the loading is increased, the penetration decreases. This latter relationship can be attributed to the combined factors of particle-liquid interactions and the effects that the definition of $\bar{q}$ has on slurries. The momentum flux ratio depends explicitly on the density of the slurry. This dependence upon the density is noteworthy since two jets with the same $\bar{q}$ but with different loadings (or densities) will possess two different jet velocities.

Further studies of the penetration were performed by light extinction methods. A liquid jet and a slurry jet of 40% loading were investigated. The momentum flux ratio of both jets was seven. A high level of extinction (absorption) corresponds to a high concentration of particles. The pure liquid jet penetrated further and absorbed more light than the slurry jet. Furthermore, the extinction curve for the two jets have similar profiles except for the slopes on the upward part of the jets. The pure liquid jet has a steeper slope (i.e., the extinction decreased more rapidly) which corresponds to a sharper penetration profile on the streak pictures.

From the nanoflash photographs the particles are shown to penetrate 40-45% farther into the air stream than the liquid portion of the jet. This figure agrees well with the results of the extinction experiment. In the extinction data, material was discovered in both jets above the penetration height. This finding poses an interesting question: if the material above the penetration height is composed of solid particles in the slurry jet, then what composes the

material above the penetration height for the liquid jet? A possible answer is that large water droplets penetrate beyond the "penetration height" and are quickly broken into very small droplets. The resulting droplets may be too small to be noticable in the photographs.

The break-up process of the slurry jet was noticably less violent than its pure liquid counterpart. The lessening of the violence could be seen in the raw data for the extinction tests which consisted of the time variation of the beam intensity. The amplitude of the fluctuations for the slurry jet were dramatically less than those for the pure liquid jet. There was up to a 50% difference in the amplitudes, the average difference being of the order 15-20%. Re-examination of the nanoflash pictures suggests that the slurry jets were indeed more steady than the liquid jets; there appears to be fewer "slotches" in the slurry plumes.

The particles that separated from the liquid plume were actually agglomerates of particles. These clumps of particles ranged from 25 to 40 microns in diameter. Particles larger than 25 or 30 microns separate from the jet; particles that are smaller than 5 or 10 microns remain locked in the jet; intermediately sized particles remain within the jet but are displaced upward.

From close examination of the nanoflash pictures, approximately one eighth of the particles separated from the liquid plume. This figure was calculated by counting the number of particles visible within a vertical strip on some selected photographs. This number was checked by first computing the flow rate of particles as known from $\bar{q}$, the loading, and the orifice diameter. By assuming an average, constant particle velocity, the number of particles that should have been present in the vertical strip was then calculated. The calculated number agreed favorably with the counted number, thus justifying this rather crude technique.

Water was contained within the separated agglomerates. In several nanoflash pictures, water can be seen being sheared away from the particles. The shearing is visible in the comet-like structures: the "head" of the comet is the agglomerate and the "tail" is formed from the water as it was sheared away.

Impinging-Jet Injector Studies

A study was undertaken to determine the feasibility of utilizing jet impingment to enhance atomization in a supersonic crossflow situation. Two angled jets impinged such that the resultant jet issued perpendicular to a supersonic airstream. The resulting plume was carefully examined to determine penetration and the droplet size distribution. Identical tests were performed with a circular injector of equivalent area to determine the relative success of the new configuration. All tests were performed in the Virginia Tech 23 x 23 cm. supersonic wind tunnel at a Mach number of 3.0. The freestream stagnation pressure and temperature were held at 4.35 atm. and 300°K respectively. The detailed results are given in AIAA Paper No. 81-1375.

This study showed that using impinging jets in a high-speed gas crossflow as a method of enhancing fuel atomization is very attractive. Not only is greater atomization achieved compared to a single, circular injector, compare Fig. No. 4 with 5 and 6, but penetration can also be substantially increased. Excellent results were obtained with $\bar{q}$ ($\equiv \rho_j V_j^2/\rho_\infty V_\infty^2$) = 12 (see Figs. No. 7 and 8) especially with the jets aligned with the free stream, producing droplets on the order of 10 μm and finer. Since the benefits derived from this technique are obvious, additional research would certainly be in order. Varying the injector geometry to determine an optimum arrangement (injection angle, etc.) should be undertaken, as well as testing under hot-flow conditions. Considering

the improved performance of such a simple scheme, impinging jets could find wide applications in all types of air-breathingengines where cross-stream injection is utilized.

Professional Personnel

Dr. Joseph A. Schetz

Dr. Antoni K. Jakubowski

Interactions

Various groups in government, universities and industry continue to use our published results for design and to support further research. During this Grant, we have been directly contacted by engineers from the General Electric Research Labs., Hoffman-LaRoche, Inc., Garrett/Airesearch, Kimberly Clark Corp., Atomic Energy of Canada, Ltd. and Atlantic Research Corp.

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Table I

Mean Droplet Diameter Variation in the Plume for Pure Water

Diameter = 0.45 mm.
Injectant: water
μ = 1.005 centipoises
σ = 73.05 dyne/cm.
$\overline{q}$ = 12.0

x/d	y/d	h/d	D_{32} (micron)
10.93	8.3	16.4	-
21.9	9.84	19.7	23.5
32.80	10.50	21.3	21.0
54.4	11.37	23.0	18.9
109.4	6.6	24.0	12.1
109.4	12.0	24.0	14.1
109.4	21.87	24.0	13.0
207.7	6.6	24.0	12.2
207.7	12.0	24.0	14.4
207.7	21.87	24.0	14.8

Table II

Mean Droplet Diameter
Variation in the Plume
for Pure Water

Diameter = 0.96 mm.
Injectant: water
μ = 1.005 centipoises
σ = 73.05 dyne/cm.
$\bar{q}$ = 4

x/d	y/d	h/d	D_{32} (microns)
5.2	4.6	9.3	-
10.4	5.5	10.9	19.0
16.1	6.2	12.1	18.5
26.8	6.5	14.0	23.2
60.0	3.1	14.5	14.0
60.0	6.2	14.5	14.0
60.0	8.3	14.5	23.3
60.0	12.4	14.5	20.8
60.0	15.5	14.5	14.2
93.2	3.1	14.5	17.3
93.2	6.2	14.5	19.2
93.2	8.3	14.5	23.5
93.2	12.4	14.5	22.9
93.2	15.5	14.5	10.0

Table III

Mean Droplet Diameter Variation in the Plume for 64/36 Water/Alcohol

Diameter: 0.45 mm.
Injectant: water/alcohol
μ = 1.005
σ = 33.5 dyne/cm.
$\bar{q}$ = 12

x/d	y/d	h/d	D_{32} (microns)
10.9	8.1	16.1	11.0
21.9	9.8	19.7	14.4
32.8	10.7	21.4	15.0
59.0	6.6	23.1	14.0
59.0	11.6	23.1	15.4
59.0	19.7	23.1	12.0
59.0	26.2	23.1	8.0
109.2	12.0	24.0	13.5
196.8	6.6	24.0	10.0
196.8	12.0	24.0	14.0
196.8	19.68	24.0	12.9
196.8	26.2	24.0	10.0

Table IV

Mean Droplet Diameter
Variation in the Plume
for 40/60 Water/Glycerine

Diameter - 0.96 mm.
Injectant: water/glycerine
μ = 9.045 centipoises
σ = 73.05 dyne/cm.
$\overline{q}$ = 12

x/d	y/d	h/d	D_{32} (microns)
10.4	8.6	17.2	26.3
15.5	9.6	19.3	23.8
25.9	9.9	19.8	23.6
60.0	5.2	23.3	17.4
60.0	10.4	23.3	24.5
60.0	15.5	23.3	18.7
60.0	20.72	23.3	19.1
60.0	25.9	23.3	22.0
60.0	31.0	23.3	16.8
93.2	5.2	23.3	22.0
93.2	10.4	23.3	21.1
93.2	15.5	23.3	22.0
93.2	20.72	23.3	21.3
93.2	25.9	23.3	24.0
93.2	31.0	23.3	17.0

TABLE V - PENETRATION HEIGHT (in mm) AS A FUNCTION OF LOADING AND $\bar{q}$

	LOADING				
$\bar{q}$	0%	3%	17%	33%	50%
2	12.0	11.6	10.8	10.2	
4	13.5	13.3	12.2	12.0	11.6
6	17.0	16.0	14.0	14.5	14.2
8	19.2	18.6	16.5	16.5	16.2
10	22.2	20.5	19.5	17.8	18.0

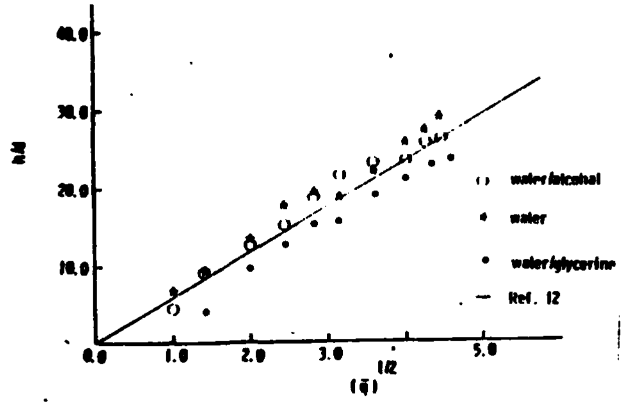

Figure 1. Penetration vs. Dynamic Pressure Ratio ($\bar{q}$)

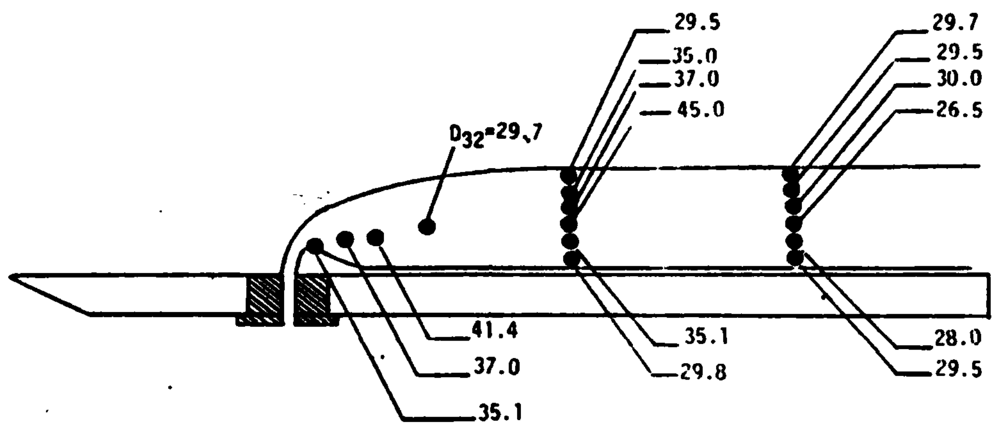

Figure 2. Full Scale Schematic Illustration of Droplet Diameter Variation in Table II.

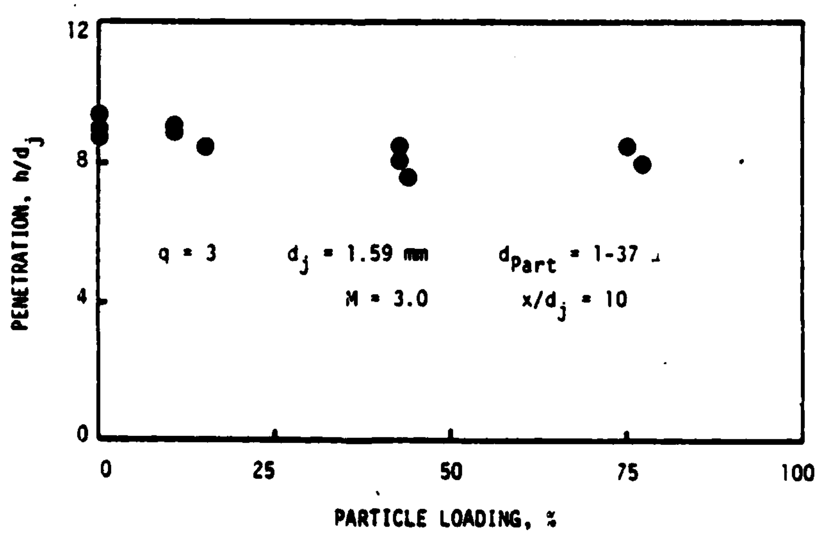

Figure 3. Penetration of the Liquid Plume vs. Loading for q = 3.0.

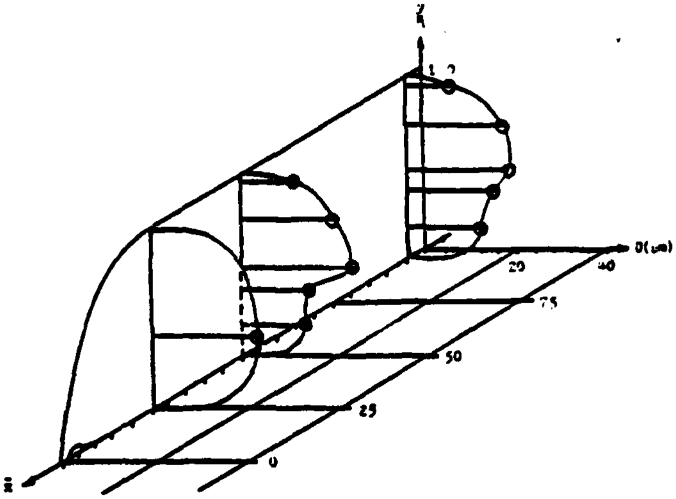

Fig. No. 4 - Droplet Distribution in Plume: Circular Injector, $\bar{q}$ = 4

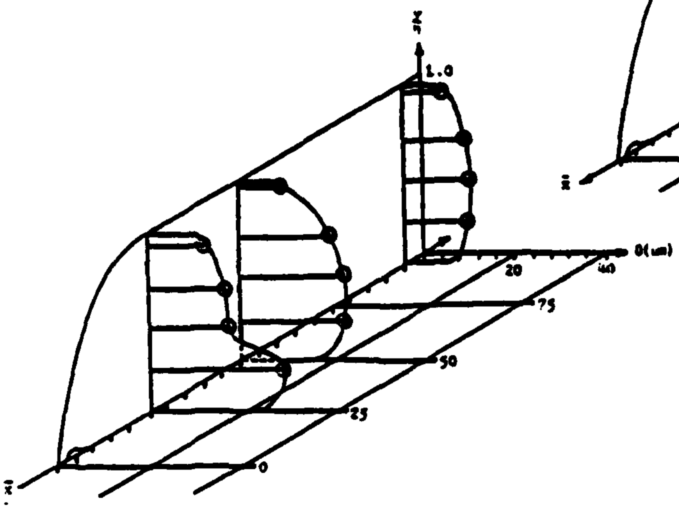

Fig. No. 5 - Droplet Distribution in Plume: Transverse, $\bar{q}$ = 4

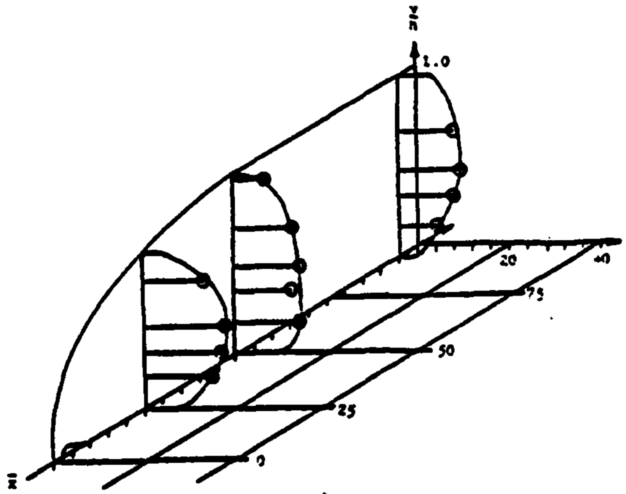

Fig. No. 6 - Droplet Distribution in Plume: Transverse, $\bar{q}$ = 12

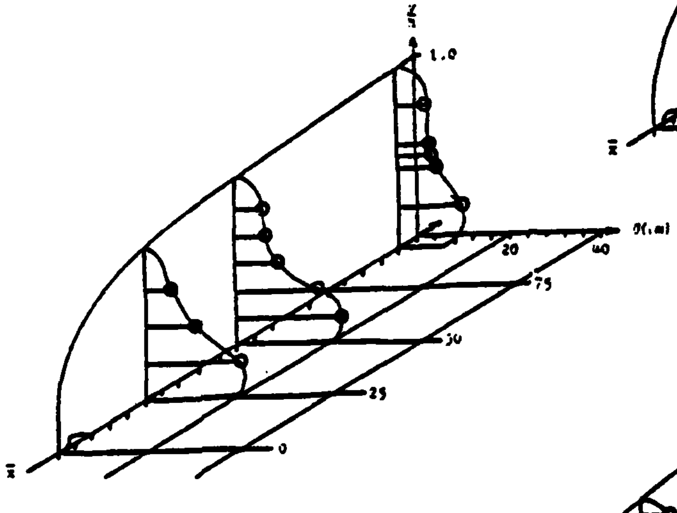

Fig. No. 7 - Droplet Distribution in Plume: Aligned, $\bar{q}$ = 4

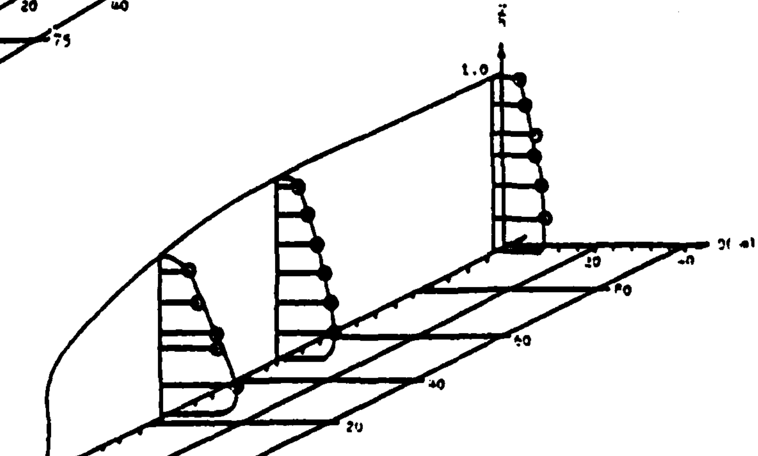

Fig. No. 8 - Droplet Distribution in Plume: Aligned, $\bar{q}$ = 12